36p.

N64-19990
CODE-1
NASA CR-53636

OPTICAL SPACE COMMUNICATIONS SYSTEM STUDY

FINAL REPORT

VOLUME I

SUMMARY, CONCLUSIONS, RECOMMENDATIONS

CONTRACT NO. NASw-540
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

SPACECRAFT DEPARTMENT
GENERAL ELECTRIC

N64 19990

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Contract No. NAS w-540

Office of Advanced Research and Technology

Headquarters

National Aeronautics and Space Administration

March 3, 1964

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SECTION 1

SUMMARY

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This study has been concerned with the ultimate potential of optical space communication and the problems of realization. The overall conclusions and recommendations are presented in this volume.

The approach taken was to perform a preliminary analysis of three assigned missions, with the object of identifying the salient advantages and problem areas of optical communciation in general. This analysis is summarized in Section 1, Volume II.

The considerations brought out by the preliminary system analysis lead to the identification and treatment of a number of significant tasks. These dealt with a wide variety of environmental and equipment factors, and are summarized in Volumes II and III. In order to assess the ultimate potential of an optical communication system, the theoretical information capacity of a noisy quantized wave was derived in Section 8, Volume II.

The theoretical performances of the major types of receivers (Heterodyne, Homodyne, and Quantum Counter) were analyzed and interpreted in Volume II, Sections 9 and 10. Volume III treats propagation in the atmosphere and special considerations in low level photo-detection. Volume IV justifies selection of heterodyne detection, and analyzes component requirements in a heterodyne communication system. This system is applied to the following missions of interest, and the performances are calculated.

- Mars - Earth Terminal
- Mars - Earth Satellite
- Moon Base - Earth Terminal

The results of the performance calculations are presented in Tables III-V, in Section 4, Volume IV. General conclusions and recommendations for future work are given in this volume, Sections (2) and (3). Interim conclusions and recommendations will be found in context in the following Volumes. Author

SECTION 2

CONCLUSIONS

It has been found that optical communication in space offers a remarkable potential for efficient data transmission. Realization of this potential, which is about 60 db better than radio, will greatly enhance the scope and value of space exploration. In solving the problems which stand in the way of realization, valuable contributions will also be made in a number of related scientific and technological areas. On the other hand, the present strong activity in optics for military and industrial applications can be expected to contribute valuable fall out to the task at hand.

This study has been directed toward a verification of the potential of optical communication in space, an evaluation of the alternative approaches which present themselves, and a specification of the work which must be done to realize a useful potential

The potential advantage of optical communication has been amply demonstrated by the results of the Final System Study and by the results of other contributors in the same area. It has been shown that a system can be constructed in principal that approaches the theoretical limit of efficiency. This system is capable providing real time television transmission from the range of Mars with a transmitted power of about one watt. Without minimizing the problems which remain, it is fair to say that the implementation of this system lies within the scope of engineering improvement rather than scientific break-through.

The selection of a recommended approach reduced to a choice between heterodyne or amplitude responsive detection, and quantum counting or energy responsive detection. The issue has wide implications, since nearly every component in the system is drastically affected. It was soon found that the alternatives have roughly equal potential performance, and the choice thus became one of evaluating the problems of realization. In opting for heterodyne detection, we are influenced by many factors, ranging from substantive evaluations of known difficulties, to a preference for the elegance of the approach. It is certainly true that heterodyne detection is an area which deserves attention in its own right.

The study has necessarily been addressed to the optimum system. This is certainly appropriate when dealing with deep space communication. The utility of sub-optimum systems which may be implemented at an early date must not be overlooked. Many applications can and should be implemented soon. For deep space missions and other high performance application, where the on-board equipment is of primary concern, the fact must be faced that available components will not make a competitive system in most cases. Fortunately, the present rate and direction of component improvement indicates a fairly early realization of a nearly optimum system.

SECTION 3

DISCUSSION OF RECOMMENDATIONS

The following recommendations proceed from the primary recommendation that the development of a heterodyne deep space optical communication link be initiated. In effect this program has already been launched by the execution of the present study and others, and by the current and proposed programs under NASA on acquisition and tracking, detection, and laser improvement.

The overall program must account for technical development on a national scale, and should therefore emphasize those tasks which are not likely to progress unless specifically directed. In logical sequence, crucial or doubtful items should receive early experimental verification, theoretical concepts should be expanded and refined, and when results justify it, major development programs should be undertaken.

The following program descriptions constitute a recommendation for future work on problems which have been identified as critical in optical space communication, but which lie outside of the scope of the present program. The content of the recommendation is by no means comprehensive but includes those areas considered to be necessary for future major decisions.

The heavy experimental content of the programs reflects the need for experimental verification of assumptions which have been made in the present study and which will be used in future analysis. It will be noted that the experiments are not directly concerned with device development, but rather with the demonstration of new principles and the acquisition of new data on natural phenomena. Emphasis is placed on well-instrumented basic experiments rather than on elaborate full-scale demonstrations.

We group our recommendations under categories relating to major subsystems. The order of presentation is intended to suggest a sequence of performance. There are seven major tasks in the following recommendation:

- Wave congruence in optical heterodyne detection
- Photo-detector improvement
- Laser and modulator
- Collector optics
- Acquisition and tracking
- Laser transmission through the atmosphere
- Theoretical system and physical analysis

Together with other tasks known to be initiated or planned by NASA, these programs will provide a balanced and logical contribution to the long-range goals of NASA in space communication.

Prior to the description of the recommended programs, some discussion in addition to that in the body of the report is appropriate and is presented forthwith. The recommended programs follow in Section 4.

I. WAVE CONGRUENCE IN OPTICAL HETERODYNE DETECTION

It has been shown in the Optical Space Communication Study and elsewhere,[1] that the use of coherent detection imposes a severe requirement on the congruency of the signal and local oscillator waves in the region of interaction.

Efficient heterodyne or homodyne detection requires that the signal wavefront entering the receiver aperture must have and retain a degree of collimation approaching the diffraction limit of the receiver aperture. This means that the beam in passing through the receiver optical system must always be capable of producing a diffraction limited image of the point source of the signal.

1. C. J. Peters, "Gigacycle Bandwidth Coherent Light Traveling Wave Phase Modulator". Proc. IEEE Jan., 1963, pp. 147-153

Transmission through the atmosphere causes the originally plane wavefronts of the signal to be bent and tilted by refraction. This causes blurring and dancing respectively of the received signal image. The wavefronts may be further distorted by imperfections in the optical system so that the image of the signal will not focus to a diffraction limited spot in the focal plane. The combined effect of atmospheric refraction and optical system imperfections is sufficient to seriously reduce the efficiency of heterodyne or homodyne detection.

If heterodyne detection is to be considered for earth terminal reception in a space communication link, some means must be found to overcome the effects of atmospheric refraction. Furthermore, if large aperture collecting mirrors are to be used in these systems, it is highly desireable to relieve the requirement for diffraction limited optical quality. We herein present an approach to the problem of wave congruence in heterodyne detection. A program of analytical and experimental investigation is outlined which will evaluate and demonstrate the principles of several possible techniques.

In optical heterodyning, wave amplitude is detected, rather than wave intensity as in the quantum counter class of detectors. In this sense, optical heterodyne detection is closely related to radio detection. In radio reception, the requirement for spatial coherence is illustrated by multi-path fading, where destructive interference occurs at the receiver aperture, and by receiving antenna gain degradation caused by destructive interference at the antenna feed. In the latter situation, the theoretical antenna gain is not realized because of errors in the figure of the collecting dish.

In optical heterodyning, similar phenomena are present, but the effects are more severe because the diffraction limited resolution of the optical system exceeds the atmospheric refraction effects. In the Optical Space Communication Systems Study, Second Report, pp 21-28, it is shown that a phase shift between the signal and local oscillator waves is transformed into an equal phase shift in the intermediate frequency current.

Therefore, if the instantaneous phase between the signal and local oscillator waves varies point-by-point over the area of interaction (the photo cathode), there results an equal local variation in the instantaneous phase of the difference frequency photocurrent which is generated at each corresponding point.

If the difference frequency photocurrent is then summed over the area of interaction, partial cancellation will occur in the sum current due to the phase differences; the degree of cancellation will depend on the magnitude and distribution of the instantaneous phase between the incident signal and local oscillator waves. It follows that the magnitude of the collected difference frequency photocurrent, and therefore, the gain of the detection process, depends critically on controlling the relative phase of the interacting signal and local oscillator waves at all points on the photo-cathode.

A similar situation exists in homodyne detection, where the signal and local oscillator have the same frequency. It is perhaps easier in this case to visualize the static interference pattern which results from super-imposing signal and local oscillator waves. In the homodyne detector, the signal and local oscillator waves are superimposed on the photo detector surface. Since they have the same frequency, a stationary interference pattern is formed. In the regions of constructive interference, the sum intensity increases with the signal amplitude, in the regions of destructive interference, the sum intensity decreases the same amount. If the areas of constructive and destructive interference are nearly equal, as would be the case when a large number of fringes are present, the total photocurrent will not respond to changes in the signal amplitude. It is therefore necessary that the number of fringes be kept small. But this is the same requirement that was deduced for heterodyne detection.

From the discussion of homodyne detection, it can be seen that a basic solution is to dissect the interference pattern into a number of elements so that the interference in any given element is predominantly either constructive or destructive. The number of elements required is on the order of the number of fringes in the interference pattern. The photocurrent emanating from each element of photo-surface will be responsive to signal modulation, but with polarity, depending on the constructive or destructive character of the interference in that element. It is therefore necessary to remove the polarity of the elemental photocurrents by squaring or rectification before they are linearly summed to produce the detected output.

The same argument applies to heterodyne detection, except in that the interference pattern is moving across the photosurface at a rate proportional to the difference frequency. The polarity of the elemental photocurrents, now manifested in the I.F. phase, must be removed by rectification or squaring before linear summation takes place.

Before further discussion of remedial techniques, a qualifying remark is in order. It was recently pointed out[2] that under special circumstances, the requirement for diffraction limited wave congruence does not necessarily include a requirement for corresponding <u>alignment</u> accuracy between the signal and local oscillator sources. In a diffraction limited image of a point source (Airy disc), the wave fronts are normal to the central ray of the converging beam. If the signal wave is so focussed, and the local oscillator wave is plane in the area of interaction, the alignment is only critical as it affects relative phase across the Airy disc.

The aperture Y in the Optical Space Communication Study is now the diameter of the Airy disc. The alignment angle is of the order of one degree for acceptable detection gain. This means that ordinary pointing errors will not affect detection gain. Also, image <u>dancing</u> as distinguished from scintillation and blurring, will not be deleterious. It should be emphasized that the requirement for diffraction limited signal and local oscillator waves and for corresponding optics quality is in no way relaxed.

It has been stated that one method of overcoming the effects of atmospheric refraction and optics imperfection is to dissect the signal into a number of elements, and demodulate each signal element independently before final summation. If atmospheric refraction causes blurring or defocussing so that the signal source subtends an apparent angle α , the sub-aperture corresponding to an element must be of the order of λ/α in diameter In such an aperture, the blur circle will be about the same size as the diffraction spot, which is the approximate requirement for wave congruence.

2. W. S. Read and D. L. Fried "Optical Heterodyning with Non-critical Angular Alignment" Porc. IEEE, Dec., 1963 p. 1787

If the blur circle is taken as 10^{-5} radians (2 arc seconds), and the wavelength as 1 micron, the element aperture must be on the order of 0.1 meters. In an earth based terminal, the collection aperture is usually assumed to be least 1 meter. For a 1-meter aperture, there would be required about 100 elements.

There are several possible methods to accomplish the desired image dissection.

The receiver could comprise say 100 independent collecting optics, each with its own photo detector and demodulator. All elements would share a common local oscillator source, and the demodulated outputs of all elements would be summed. Phase shifts incurred in distributing the local oscillator power among the elements would be of no importance. The small size of the element optical systems would make it relatively easy to provide diffraction limited optical quality. The large number of photo-detectors and demodulators would be expensive. There would also be a problem in increased noise resulting from the use of multiple detectors and demodulators.

Rather than dissecting the signal at the collecting aperture, the dissection could be accomplished at the photo-surface. The signal wave could be collected and re-collimated at a smaller aperture by a single optical system, then superimposed on the photo-surface with the collimated local oscillator wave. The photo-surface could consist of a mosaic of independent detectors, each driving a demodulator. The demodulator outputs would be linearly summed to form the detected signal. The area of the mosaic could be conveniently large, limited by the dark current contribution of the photo-detector surface. This problem (detector noise) is minimized by the large process gain of heterodyne detection. It would be necessary to provide a large fraction of active detector area in the mosaic to prevent loss of signal "in the cracks". This suggests a variation in which the reduced and recollimated signal wave is focussed on to an array of photo-detectors by a small mosaic of lenses.

Carrying the concept a step further, one might perform the signal dissection in the demodulator. The reduced and recollimated signal wave and the local oscillator wave would strike a photo-emissive extended target as in an image orthicon. The resulting photoelectron image would be focussed on a target. The target would collect the photo-electron and without lateral current flow, perform a squaring process on the intermediate frequency component, then sum the demodulated signal across the target area. Electron image magnification could be used to adjust the size of the target relative to that of the photo-cathode.

It would even be possible to enlarge and dissect an image the size of a diffraction spot.[2]

Although a photomixer image tube[3] has been constructed, it was of the sequential scanning type and is not adaptable to this application. The unique feature of the proposed tube is the target. The target must collect the photoelectrons, demodulate the elements of photocurrent without cross-talk, and sum the demodulated signal. If the number of elements is in the order of 100, a wired assembly of collector plates, diodes, bandpass filters, and summing networks is conceivable. If the number of elements is in the order of 1000 or 10,000, as it might be for very large apertures, film deposition and micro-electronic techniques should be considered. The most obvious method of demodulation is by use of a square law diode. However, the non-linear action of secondary electron emission should also be considered as a possible means of demodulation.

It should be noted that there is a requirement for an IF bandpass filter in each element. This poses a difficulty, especially in a micro-miniaturized mosaic. In homodyne detection, all processes are similar except that the bandpass filters are replaced by low pass filters.

In contrast to the signal dissection techniques, there is an approach wherein the phase errors are corrected before demodulation. The correction could occur in the signal optics, the local oscillator optics, or in the I.F. photocurrent. Regardless of where the correction is performed, it is necessary to measure the phase error in each elemental part of the signal in order to control the correction process. For example, in the previously described array of independent collecting optics, the I.F. component of each detector would compared in phase to a reference, and continuously corrected by a phase shift control circuit. Alternatively, the phase correction could be by mechanical or electro-optical means in the optical paths of the element optical systems.

The signal level in a single detector of a 100-element array would be 20 db below the total signal. In principle, the phase measurement could still be performed providing that the phase control loop bandwidth is at least 100 times less than the channel information bandwidth.

3. R. F. Lucy "An Experimental Photomixer Image Tube" Proc. IEEE, 1963, pp 162-165

The phase corrected IF components would finally be summed, and demodulated in a common demodulator. The use of a common demodulator, operating at higher signal level than the elemental demodulators required in the signal dissection techniques, is an advantage in terms of noise level.

Still another phase correction technique has been considered. The superimposed signal and local oscillator waves are incident on a photo-emitter and a photo electron beam results in which the IF current appears as a longitudinal electron density modulation. The phase error in the incident light results in bending of the electron density wave fronts in the beam. The beam then interacts with an externally generated traveling wave which is moving at beam velocity and is synchronized with the IF so that the traveling wave is stationary with respect to the electron density wave. It is supposed that the traveling wave may interact with the electron beam so as to correct the curvature of the electron density wave fronts in the beam. It is further supposed that the waves will not exchange power at the IF. The phase error having been corrected, the electron beam passes into a TWT amplifying structure where the IF component is amplified and extracted.

Several potential techniques have been herein described for the correction of wave front distortion in coherent reception. Two broad categories exist: the phase is either corrected before a common demodulation process, or the signal is demodulated in discrete parts, then recombined. Several variations of both categories have been discussed.

In weighing the merits of the two basic approaches, it is evident that key problems exist for each. We identify these problems as follows:

A. <u>PHASE CORRECTION TECHNIQUES</u>

1. The TWT phase corrector is by no means theoretically substantiated, and would be of novel design and construction.

2. The alternative phase correction techniques all require phase detection at a signal level well below the received signal level.

3. A large number of phase detection and phase correction devices are required.

B. DISCRETE DEMODULATION TECHNIQUES

1. Demodulation of discrete signal elements occurs at very low signal level. Noise contribution of individual demodulators must be held to a level perhaps 20 db below normally acceptable levels.

2. For heterodyne detection, a large number of IF bandpass filters must be provided. This requirement is less severe in homodyne detection, since low pass filters are used.

The severity of most of these problems depends on the number of elements required. Assuming that the estimate of 100 elements is approximately correct, discrete optical and circuit elements are practical. If the number of elements approaches 6600, as estimated in the Optical Space Communication Study, Second Report, p. 28 for a larger collector and a shorter wavelength, such means become less desireable.

The present status of optical heterodyne detection is as follows:

1. The problem of wave distortion has been identified, theoretically analyzed for certain cases, and experimentally verified for certain cases.

2. Several remedial measures have been postulated and briefly evaluated.

3. The probable importance of the problem in practical situations has been evaluated and found to be significant.

II. PHOTO-DETECTOR IMPROVEMENT

A. QUANTUM EFFICIENCY

A photo-detector is simply a device which, through an interaction between light and matter, provides an electrical signal proportional to the light flux falling on the photo-sensitive material. The proportionality constant, for a given interaction, between the electrical signal and an incident light flux is called the quantum efficiency.

It is defined as the ratio of the number of photoelectrons produced in a radiation sensitive process to the number of incident photons available. The quantum efficiency of a light sensitive material may also be represented as the probability that an incident photon will produce a photoelectron in an interaction between light and matter.

The quantum efficiencies of existing photosensitive materials are well known and considerable data is available which allows the direct comparison of many of these. For example, the graph of Figure 2 on page 5-3 of the First Optical Communications Study Report shows a comparison between the approximate quantum efficiencies of a number of photosensitive materials. The following table summarizes the approximate quantum efficiencies of a number of photoemissive cathodes at the wavelengths of the helium-neon gas laser (6328A^o and 11,500A^o) and the ruby laser (6943 A^o).

QUANTUM EFFICIENCY AT

Photo surface	6328A^o	6943A^o	11,500A
S-1	0.3%	0.34	0.025
S-4	0.38%	----	-----
S-10	1.05%	0.35	-----
S-20	5.%	2.6	-----

It should be noted that at the longer wavelengths, the efficiency of all the photoemitters drops off until at 11,500A^o, only the S-1 has any measurable sensitivity to incident radiation.

Many semiconductor photosensitive materials have quantum efficiencies as high as 50%, however, these devices are generally inadequate for the detection of very low light levels because of their much higher noise equivalent power. Their use as photomixers in communications systems is also limited by their small physical size, since atmospheric refraction combined with surface irregularities of large light collectors provides a circle of confusionast the focus of the optical system which is generally larger than the area of the photosensitive portion of the device.

The generally low quantum efficiency of the photoemitting cathodes is primarily due to the method of construction. Roughly only 40% of the incident light photons penetrate the photocathode surface: 30% are absorbed or reflected by the optics while the remaining 30% are reflected by the surface of the photocathode material. In addition, approximately 50% of the incident light photons which do penetrate the surface of the photocathode pass through the thin film without being absorbed. The end result is that only about 20% of the available incident light is actually available for absorption by the photocathode. The ratios of light absorbed and transmitted also vary with wavelength. In the red and near infra-red portions of the spectrum, where most lasers operate, the quantum efficiencies of the available photoemitting materials is quite low.

It is seen that improvements in quantum efficiency may be found in two areas. First, the discovery of new materials for sensitizing the photocathode or new ways of activating known materials will certainly offer improvements in quantum efficiency. Second, the presently available photoemissive materials may be used to advantage by improving the geometry and method of application of these materials. Several methods for accomplishing improvements with existing photoemission materials have been proposed. Two of the more promising techniques are described below:

1. Multilayered Photosurface

In order to make optimum use of the characteristics of the photo-emissive material, it was proposed by H. Mayer[4] in 1946 that a photocathode be prepared which arranged the photo-emissive surface in layers of material. At each layer, some of the light would be reflected, some absorbed and the remainder transmitted by the thin film. This technique provides for an improvement in the overall quantum efficiency since that portion of the light transmitted by each layer is passed through another photoemissive layer with the result that more photoelectrons can be produced for a given incident light than with a single photosurface.

The multilayered photo cathode, while offering improvements in quantum efficiency, also poses some problems which may be difficult to resolve. First, there are considerable manufacturing

4. H. Mayer, "Die Vielschichten - photozelle". Z. Physik 1946

difficulties involved with making good photocathodes in complex forms since the processes involved must be carried out by evaporating the materials in vacuum. Second, for applications in laser detection, which require very fast response times, some difficulty will be encountered in keeping photo-electron transit time distribution small. It is true that photoelectron transit time is a function of the applied voltage, however, in complex structures, it is extremely difficult to keep electric field intensity constant over all parts of the structure.

2. Absorbing Cone Photocathode

A recent proposal by a General Electric scientist combines a relatively easy to make photocathode with a geometry which will provide nearly the maximum theoretical quantum efficiency from a given photo-emissive material. This technique involves the use of a photocathode deposited on the inside of a Mendenhal cone. The Mendenhal cone is a device found in one commercial calorimeter which is used for measuring the energy output from pulsed lasers. A Mendenhal cone is simply a conical hole in a piece of metal. The inside apex angle of the cone is approximately 14^{o} and the sides of the cone are polished to provide a specular finish. This device has the property that any radiation entering the cone acceptance angle is totally absorbed through multiple reflections from the surface of the cone.

It was proposed that a photocathode be deposited on the inside surface of a metallic conical hole with proper apex angle. The result is that most of the light photons which enter the cone are absorbed in multiple reflections by the photocathode material. The only losses occur at the interface between the photoemissive material and the supporting specular surface. This device in theory should provide very nearly the maximum theoretical quantum efficiency. This device offers a relatively simple structure upon which to deposit a photocathode. Preliminary investigations indicate that the photocathode can be formed using existing equipment and techniques. In addition, the photoelectron transit time spread can be controlled very well by combinations of electric and magnetic fields.

B. DYNODE MIXING TECHNIQUES

It has been proposed by General Electric that a conventional photomultiplier can be used as a double conversion superhetrodyne. In this application, the photomultiplier is used as a conventional photomixer with the signal beam and the local oscillator beam incident upon the photocathode. Photomixing takes place and if the congruency requirements are met the beam of photoelectrons is modulated with the intermediate frequency which in turn is modulated with the information signal. The first dynode or first several dynodes, as the case may dictate, are modulated with the second local oscillator frequency. Since variations in dynode voltage produce variations in the gain of the multiplier section, mixing will take place between the first intermediate frequency produced by the mixing of the two light beams and the second local oscillator frequency to produce a difference frequency which is the second intermediate frequency. An almost exact parallel to the type of mixing may be seen in the operation of the pentagrid converter which is popular in commercial radio receivers. The second intermediate frequency is now amplified along with the photocurrent in the remainder of the dynodes.

This technique will allow for the detection of relatively high first intermediate frequencies by conventional photomultiplier tubes. Most photomultipliers cut off below 300 megacycles and only a few can respond to signals in the region of 450 megacycles. The time spread distribution of the photoelectrons from a good photocathode is very narrow, and most of the time spreading, which is primarily responsible for the fast rolloff of frequency response in photomultipliers, occurs further on down the dunode chain. Therefore, if the second IF is low enough so that the multiplier chain can handle it without undue attenuation, we have effectively increased the bandwidth capabilities of the photomultiplier in photomixing applications. In addition, some conversion gain can be realized from the second mixing operation. This technique is particularly attractive since the well-shielded photomultiplier receiver is not plagued by the complex image problems encountered in conventional double conversion superheterodyne radios.

III. LASER TRANSMISSION THROUGH THE ATMOSPHERE

A. THE ATMOSPHERE AND LASER SPACE COMMUNICATION

Any application of the laser for communication between a space vehicle and earth automatically suggests that one of the terminals be on the earth itself. Such an earth terminal, however, requires that the laser beam travel through the earth's atmosphere. As the following discussion indicates, a trip through the atmosphere can cause some drastic changes in this laser beam and create some formidable problems for the laser receiver.

The basic effects which must be considered can be classified as follows:

1. "Seeing" effects
2. Absorptive attenuation
3. Scattering (nonabsorptive attenuation)
4. High energy effects
5. Background noise

Fortunately, the problem of transmission of light through the atmosphere has been of great concern to astronomers and has received some prior attention. Therefore, there are data available which allow an estimation of many of the effects of the atmosphere on a laser beam. This data will now be examined and recommendations will be made on how to expand, supplement, and apply this data to the laser space communication problem.

B. DISCUSSION

1. "Seeing" Effects

To the astronomer, the problem of "seeing" through the atmosphere places limits on the accuracy of position determination, the brightness of detectable objects and the resolution and contrast of his observations. The twinkling of a star may be a joy to a child but it is a problem of major proportions to the astronomer and will be a major problem to the designer of space laser systems where the laser beam will traverse the atmosphere. The general term, twinkle, can be broken into the following components:

1. Scintillation
2. Dancing
3. Pulsation (defocussing)
4. Rotation

Scintillation refers to an amplitude modulation or multiplicative noise impressed on the light signal by the atmosphere. This is easily observable with a star focussed on a photodetector. Scintillation frequencies have been observed as high as 1000 cycles per second. There is a strong correlation between this effect and the wind velocity near the tropopause. Scintillation can be shown to be spatially incoherent over very small angles. Measurements with two seconds of arc separation between two stars have shown very little correlation in this effect. This effect can therefore be averaged out for larger apertures or for large sized observed objects. For some tracking missions or communication systems of very small information bandwidth, this effect could also be averaged out in time.

If one removes the eyepiece of a telescope and looks at the aperture, the turbulence causing the scintillation can be seen. There are elements varying from roughly an inch or two in dimension to areas larger than six or eight inches. These elements, as carried by the winds near the tropopause, can be seen to stream past the aperture. A frame-by-frame examination of motion pictures taken of the phenomenon reveals practically no correlation from frame to frame. Thus, the turbulent elements are changing size and shape more rapidly than they are carried past the aperture. It appears that these fluctuations in the elements take place in less than thirty milliseconds. There are then two sources of scintillation modulation. The first is the turbulence of the atmosphere and the second is the streaming of this turbulence across the aperture as it is carried by the wind. As a first approximation, at least, these effects appear to be independent. In the design of an optical communication system, this effect would be considered as an additional source of fluctuation over the photon noise inherent in the system.

As a star is observed with higher and higher powers, it begins to dance back and forth about some mean position in a random manner. A time exposure with a photographic plate or other detector gives a large image, but a fairly accurate position can be determined by the averaging process. Very short exposures yield a fairly sharp image but an indefinite position. Scintillation and image motion were in the past thought to be closely related, but recent experiments have established that they are actually independent. Image dancing is highly correlated over an appreciable spatial field. Star dancing is attributed to refractive effects in the turbulence of the lower atmosphere near the observer. As an extension, the refraction by the atmosphere, which increases as elevation angle is decreased, can be considered as a d.c. component of the image dancing phenomenon. For very narrow receiver beamwidth optical communication systems, this effect may cause some tracking problems. It may also cause some problems for heterodyne detection. Observations show the dancing is of the order of several seconds of arc.

The pulsation or defocusing phenomenon can be observed by examining the image plane of a telescope. The image of a star becomes larger and smaller in a random manner. At one instant there is a sharp image, and at a later instant there is a fuzzy image. There is not enough experimental data at this time to make a decision as to the source of this effect.

The fourth phenomenon is observed at very great magnification. The star image looks almost like a pinwheel. It slowly rotates first in one direction and then in the other with rays extending and subsiding continuously. This effect can probably be grouped with the pulsation effect and be considered as a defocussing phenomena.

As was stated earlier, these "seeing" effects will be a major concern in the design of a space laser communication system that uses an earth-based terminal. Scintillation produces a noise modulation on the signal, however larger apertures tend to average out the effect. A space laser communication system can be expected to have a good-sized aperture so that this phenomenon can be considered as a simple loss in the system gain-margin calculations. The phenomena of dancing, defocussing, and rotation will become a major problem if heterodyne detection is to be employed by a receiver. It has been recently demonstrated that dancing, meaning a tilt of the incident plane wave, is much less serious than defocussing in heterodyne reception. It is therefore important to obtain data on focussing apart from dancing.

The atmospheric effects causing the "seeing" problems appear to favor a link from a spacecraft to earth over a link from earth to the spacecraft. If the atmosphere should bend an optical signal through an angle on the pass from spacecraft to earth, the effect may not be too great due to the fairly short distance between the receiver and the location of the bending. However, if the same bending angle is imposed on the outgoing beam, the long path length to the spacecraft will cause the signal to completely miss the receiver. Pointing determined from a received beam minimizes this problem.

2. Attenuation

Consider now the attenuation of light as it passes through the atmosphere, neglecting the effects of atmosphere turbulence. As light passes through a volume of air, there will be both an absorption and a scattering of light which will remove light from the beam. The equation of transfer in such cases is given by Chandrasekher in, "An Introduction to the Study of Stellar Structure" and in other works. The continuous attenuation of a signal may be considered as consisting of molecular (Rayleigh) scattering, absorption, and some scattering by longer particles. The total transmission of an atmosphere is given, for example, by Allen, in "Astrophysical Quantities". As given there, for a clear atmosphere, 1 air mass, and 0.4μ, the transmission is 63 percent; at 0.45μ, 73 percent; at 0.50μ, 80 percent; at 0.55μ, 83 percent; at 0.60μ, 84 percent; at 0.65μ, 88 percent; at 0.70μ, 91 percent; at $.80\mu$, 94 percent; and at 1μ, 96 percent. These figures include Rayleigh scattering with by dust particles in the clear air. Since one air mass is equivalent to roughly 8 KM of air at S.T.P., this data may be directly applied for an 8 KM path in clear air. Because of this high transmission, this should not be an important factor in calculations, unless extreme ranges in the atmosphere are required.

Band absorption by atmospheric gases also exists, but at present wavelengths this is not a problem. Data on this will also be found in Allen's work.

When haze, fog, or clouds occur, the situation changes radically. The attenuation can easily become great enough to make an optical communication system ineffective. The Optical Communication Study, First Report pointed out that transmission to the earth station, through clouds, may be possible. Successful transmission in the reverse direction is less likely, however. Middleton, "Vission Through the Atmosphere" is a basic reference on the data that is available. At present, it is not possible to readily estimate attenuation by fog and clouds, and much additional work is required.

3. High Energy Effects

This topic is included as a possible problem or advantage for the earth to spacecraft link of an optical communication system. The situation here envisioned is one in which the intensity of the optical beam is sufficiently great to modify the properties of the atmosphere. There is just not enough data at present to forecase what will occur. One possibility of a problem would be increased absorptive attenuation of the signal. One possibility of an advantage would be if this energy could clear a path through haze or fog for subsequent use at lower levels.

4. Background Noise

The problem of background noise due to the atmosphere has received a great deal of attention by astronomers pushing out for fainter and fainter stars. Allen's work contains enough data for most design problems of an optical space communication system. The statistics of narrow frequency bands of this noise will be required, however, for the design of extremely low-level optical receivers.

SECTION 4

RECOMMENDATIONS

Based upon the overall results of the study and upon the discussion in the preceding section, the following described programs are recommended.

I. WAVE CONGRUENCE COMPENSATION

This is the most crucial and perhaps most difficult of the problems confronting the realization of practical heterodyne detection. It is therefore recommended for first priority in the task sequence. The approach outlined below is designed to give an early demonstration of basic concepts, followed by a broad evaluation of alternate approaches, and finally an intensive persuit of a selected approach.

1. A laboratory experimental heterodyne detection link should be set up. The equipment should be of sufficient quality to reproducibly demonstrate near optimum detection gain. This implies diffraction limited optical quality, good mechanical stability, and good laser stability.

Means should be provided for precision adjustment of beam angle and divergence, and for modulation of the signal wave.

The initial tests will demonstrate optical heterodyne detection under simple changes in angle of incidence and beam divergence. These tests will verify the theory and check the apparatus. They will be performed at high signal level to minimize noise problems at this stage. Additional verification will be obtained by relating visual interference patterns to detection gain in homodyne detection.

2. Having established an experimental basis for the phenomena, a demonstration of remedial measures should be performed. This would require the construction of a single row of a 100-element detector array. Such a one-dimensional

representation would sacrific very little generality, and would be less expensive than a full array. The initial experiments will be performed with simple detectors and optics because a high signal level will be available. Measurement of IF phase shift and sum amplitude will be made under simple changes in beam alignment and divergence.

Since the wave patterns will be static and controlled, both phase correction and discrete demodulation experiments can be performed without the complication of rapid phase changes.

3. The experiments will then be extended to include the effects of random wave front distortion. This could be generated by passing the beam through a cell of convecting water or air.

Detection gain will be correlated with a measure of wave distortion, such as the apparent size of the source. This will serve as a basis for predicting performance in atmospheric refraction conditions.

4. The problem of photo-detector and demodulator noise will be attacked by the preliminary tests with detector and demodulators. While these considerations are perhaps not directly connected with wave distortion effects, data is needed to properly evaluate the alternative techniques which have been proposed. The tests will evaluate noise level in photo-emissive and photo-conductive detectors of various types, both singly and in array combinations. Low level phase lock loop operation will be evaluated.

The relative performance of the phase correction and the discrete demodulation techniques will then be evaluated by operation of a ten-element linear array in a signal wave of known low level.

5. The foregoing experiments, together with concurrent analysis, will lead to the selection of a preferred technique. The analysis will include theory and design considerations of the TWT phase corrector, and the special image tube described above.

6. Further tests will be performed at an outside range to correlate the laboratory result with natural atmospheric effects. These tests will be evaluated with the aid of concurrent atmospheric propagation tests to provide an estimate

of the performance of a full scale space communication link. An important result will be an estimate of the number of elements required in a practical space communication situation.

In the course of the experiments and analysis, information will be gained on related problems and requirements, such as laser oscillator line width, stability, and off-mode radiation, frequency shift due to atmospheric turbulence, and the effects of amplitude scintillation and polarization shift in the atmosphere.

II. PHOTO-DETECTOR IMPROVEMENT

Although the photo-conduction detector has a present advantage in quantum efficiency and appears to be well stuited otherwise for heterodyne detection, its adaptibility to the requirements of wave congruence compensation is not known and will not be known until the previous task is well underway. It is recommended that the following limited work be done on the photo emission detector as a backup for photo-conduction.

It must be noted that there are fringe benefits accruing from the work proposed below which are applicable to areas of engineering other than the detection of laser beams.

1. Absorbing Cone Photocathode

It is recommended that a study program be instituted to develop and describe the capabilities of the absorbing cone photocathode. The study will explore the expected improvement in quantum efficiency, the geometry of the cone, and the photo-electron optics problems. Techniques and methods for focussing, accelerating and multiplying the photoelectrons will be established. Samples of the cone photo-cathode will be prepared in the laboratory and sufficient measurements made to fully describe the capabilities of the photocathode.

2. Dynode Mixing Techniques

It is recommended that a study program be to investigate the capabilities of photomultiplier tubes instituted as dual conversion superheterodyne receivers for optical mixing applications. The gain versus dynode voltage characteristics of existing photomultiplier tubes will be investigated as well as the gain versus focussing and acceleration electrode voltages of existing photomultiplier tubes. A series of experiments will be designed in which existing tubes are tested as dynode mixers and the results applied to the postulation of an improved tube in which the dynode structure is optimized not only for optimum gain and time spread but also for optimum conversion gain. In addition, the desirability of adding or altering the placement of mixing electrodes between the photocathode and the dynode structure will be investigated.

The study should allow for the assembly and test of an improved tube if the result of the experimental tests and the study of capabilities indicate that such a step is warranted.

III. LASER AND MODULATOR

This study has not looked deeply into the matter of laser design, except where the output characterization or the mode of modulation made it necessary. We note that our transmitting laser resembles a gas laser in every respect except available average power, where it exceeds most gas lasers by a factor of about twenty times. We feel that laser design will progress nearly independently of our recommendations, and do not specifically recommend basic laser development as a follow-on to this study. Recent developments in gas lasers promise great improvement in efficiency and average power. Should these prove successful, the requirement will be met. On the other hand, the injection diode laser has already achieved the required average output power, together with a quite acceptable efficiency.

Work is proceeding at General Electric to determine and improve the stability and line width of the injection diode laser. It is entirely possible that our hypothetical laser may turn out to be an injection diode.

We recommend that developments in these areas be carefully monitored. The FSK modulation scheme described above, along with other variations, should be theoretically and experimentally evaluated. An experimental FSK laser, not necessarily of high output or efficiency, should be built and operated to check the problems of stability and response speed in the proposed modulation method. A heterodyne FSK data link should be set up to evaluate the techniques of AFC without introducing the problem of wave congruence.

IV. COLLECTOR OPTICS

Deep space communication requires the use of the largest available collector on the principal of minimizing on-board equipment. It has been shown that a collector of thirty foot aperture can probably meet the resolution and reflectivity requirements of our system. We recommend that development of such a dish be initiated, not only for eventual use in a deep space communication system, but for its value in other optical, infra red, and sub-millimeter experiments. It would be appropriate to fabricate some scaled down mirrors to evaluate problems in surface finish, thermal stability, and weathering, then to proceed to the fabrication of some full scale sectors, which would permit further evaluation without the cost of a complete mirror.

Large optical collectors with diameters of up to 34 feet have been built at General Electric's Missile and Space Division. These were fabricated by spin-casting epoxy in a parabolic mold. The capabilities of this manufacturing technique were investigated and the following conclusions were drawn from the investigation.

A complete optical collector 29.5 feet in diameter can be fabricated by the spin-casting technique. It is possible, with existing equipment, to provide f numbers between approximately f/0.5 to f/6.5. The mirror would be limited to 29.5 feet in diameter by the capacity of the vacuum chambers available at the General Electric Company, which could be used for aluminizing the reflecting surface. The finished mirror would have a tangent error of not more than two minutes over 98% of its area. The surface roughness would be better than one micro-inch rms.

The collector would be fabricated by first building, or obtaining, a 29.5 foot diameter parabolic antenna with the required focal length. This would serve as the support for the epoxy surface. The surface qualities of the backing structure would not be a problem since the spin-cast epoxy would cover the surface of the backing structure. The function of the backing structure would be to support the epoxy during spinning, and to support the collector on the tracking mount. The support of the collector is the main problem to be encountered in a spin-cast collector, since the backing structure must be of sufficient rigidity to maintain the figure of the collector as varying mechanical loads, wind stress, etc., are encountered on the tracking mount.

The backing structure is mounted on the spin-casting machine and the epoxy surface is cast. Generally, three coats of epoxy are used which gives an epoxy surface which is between 3/8 and 3/4 inches thick. The completed collector would then be aluminized in a vacuum chamber, which is now in operation at the Valley Forge Space Technology Center.

V. ACQUISITION AND TRACKING

The problem of acquisition and tracking has not been extensively considered in this study, except as a factor in the assignment of transmitter beamwidth. We have considered the problem in company funded studies and have proposed programs to NASA which provide a thorough treatment of the subject. The selection of a 1 arc second transmitter beamwidth in this study was quite arbitrary, but conditioned by an estimate of realizable pointing capability. In fact, the selection of an optimum beamwidth is a very complex process, depending on an involved tradeoff between transmitter power and pointing equipment complexity. This is covered in our proposal N20238 to NASA-MSC entitled "A Proposal for a Deep Space Laser Acquisition and Tracking Study" in response to RFP No. MSC 64-913P.

We recommend that such a study be performed. The results are essential to a complete understanding and evaluation of optical space communication.

VI. LASER TRANSMISSION THROUGH THE ATMOSPHERE

A. GENERAL

There are five potential sources of experimental data pertaining to atmospheric propagation in communication between space and earth:

- Astronomical star observations
- Lower atmosphere test range observations
- S-66 satellite observations (or equivalent)
- Extra-atmospheric laser source observations or
- Observations of earth laser sources from outside the atmosphere.

None of the first three provides a complete representation of the desired space-ground laser link.

If it is deemed desirable to obtain propagation data prior to the orbiting of a suitable laser or observation platform, it is necessary to attempt a synthesis of existing and accessible information which will provide the desired data.

The recommended program will take this approach, and will be based on available data augmented by experiments to be performed in specific support of the program.

A complete representation of the space-earth communication situation must meet the following criteria:

1. The beam diameter at the receiver must approximate that of a laser beam. This is pertinent to the illumination of the receiver as the beam moves.
2. The beam must traverse the entire atmosphere.
3. The source must be nearly monochromatic.
4. The source must be stable in intensity and direction.

When these criteria are applied to the three accessible sources of data, the following results are readily obtained:

Astronomical star observations: meets two and four
Lower atmosphere test range observations: meets three and four
S-66 satellite observations: meets two and three

The deficiencies of each source must be overcome by generalizing data from one so that it can be applied to another, and by experimental techniques which supply missing factors.

B. RECOMMENDED TASKS

We recommend that all three experimental approaches be implemented thus providing mutual support and confirmation.

In all observations, the principle components of atmospheric effects, as reviewed in the introduction, will be differentiated. This is important because although the components have entirely different consequences in optical communication, they have often been confused in previous reporting. The propagation experiments described in Part I of these recommendations required special observations to relate wave congruence and image blurring. By means of these tests and appropriate analysis, it is expected that conclusions regarding heterodyne detection can be inferred prior to actual space experience.

1. Astronomical Star Observations

It is recommended that astronomical star observations be made. The criterion for monochromaticity can be met in star observations if a sufficiently narrow band filter can be used. Calculations show that a zero magnitude star can be observed at an adequate level through a filter of a few Angstroms pass band. Further calculations will show whether or not the interference phenomena of interest will be observable under such conditions.

The criterion on beam diameter places a requirement on other observations to determine the significance of a beam diameter difference as applied to the astronomical star observations.

As the astronomical star observations will be made through a night sky, extrapolation of results to daytime laser propagation must be based on other observations.

The astronomical star observations will yield data primarily on the "seeing" effects but data on background noise can also be obtained.

2. Test Range Observations

It is recommended that observations be made on a lower atmosphere test range. Results would be augmented by already available data. The criterion on beam diameter will be explored using a range of diameters for both beam and receiving aperture. It is expected that the relationship between refraction effects and the absolute and relative diameters of beam and receiver aperture can then be deduced with the aid of data from the observation of the S-66 satellite.

The criterion on traversal completely through the atmosphere can be assuaged by the use of data from other observations.

The test range observations will yield data primarily on absorption and scattering phenomena. Background noise data will also be accumulated.

3. S-66 Satellite Observations

It is recommended that observations of the S-66 or other retroreflector carrying satellite be made.

The criterion on beam diameter may be met with respect to near range applications. Its seriousness for long range applications must be deduced with the aid of other observations. Test range scaled experiments are expected to provide an approximate correction for the variance from the desired condition.

The criterion for source stability will not be met due to a variety of factors including change of reflector aspect angle, ground laser source noise and the fact that the light reflected will have just traversed the atmosphere. To some extent the effect of these factors can be averaged out or otherwise compensated, e.g., post facto corrections for laser output variation and tracking errors can be made. The remaining deficiencies are expected to be overcome with the aid of data from other observations.

In recent experiments at General Electric, it has been observed that dancing is greatly reduced in a round trip from a diffusing target, when the source and receiver are optically coincident. This experiment will be repeated on the test range for a retroreflector target, and the results used in an analysis of the S-66 experiment. The observations should also include scintillation and blurring.

The observations will provide valuable confirmation of the star and test range data.

VII. THEORETICAL SYSTEM AND PHYSICAL ANALYSES

The theoretical aspects of the information capacity of a quantized wave have been treated in the present study. This treatment covered first the theoretical information capacity of a noisy quantized wave, then compared this to the relative ability of both coherent and incoherent receivers to extract information from the wave.

Several useful and very general relations were developed, which prescribe limiting and optimum mode occupation numbers and input SNR values for coherent and incoherent detectors. These results indicate that coherent and incoherent detection may require quite different modes of modulation and encoding.[5] These results were used to describe examples of coherent and incoherent systems for comparative evaluation.

It was not possible in the present study to explore fully the implications and areas of validity of these general relationships. It is felt that new and perhaps important insights may be gained by further consideration of these general relationships.

We recommend therefore, that the theoretical analysis of coherent and incoherent reception of a noisy quantized wave be extended along the lines of the present study, to develop and use the concepts presented in that study.

In the course of the study, it became evident that certain theoretical matters were not well understood or lacked experimental verification. Not only are these topics of theoretical interest, but they may have a bearing on practical matters in optical communication. We mention two of them here and recommend that they be considered for future attention.

- The precise nature of photon interaction in heterodyne mixing is not well understood. Experiments at very low levels might demonstrate nonlinear effects due to the limited area and time of interaction of the photon wave packets.

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5. Optical Space Communication Study, Volume II, Appendices I and II.

- The statistics of photon arrival from a laser source may in some cases be different from the assumed Poisson statistics. An experimental measurement of laser photon statistics would clarify the assumptions.

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The following listed personnel have been the key contributors to this study. In addition, valuable help has been received through discussions with numerous additional General Electric personnel.

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